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Flavor Physics: Kaons, Charm, Beauty, Taus and Neutrinos

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Flavor Physics: Kaons, Charm, Beauty, Taus and Neutrinos

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The summary of the presentations at the workshop on Heavy Flavor Physics, Part II at the International Lecture and Workshop Series: "Frontiers in Contemporary Physics: Fundamental Particles and Interactions" should include a wide variety of topics in flavor physics. This paper provides a brief selection from each presentation to give a flavor of the session. Results on the production and decays of taus, kaons, charm and beauty particles are reported. The results from several experiments that have looked for neutrino oscillations at accelerator based experiments are also discussed, including new results from LSND using neutrinos produced in pion decay in flight. Projections and plans for several ongoing and future experiments in flavor physics are discussed.

Introduction

Much effort and many experiments have been directed at measuring the elements of the quark-mixing matrix. One of the major challenges that remains is the confirmation the CKM matrix [1] explanation for CP violation. In this session, there were many presentations on many different aspects of flavor physics. This paper will try to summarize the work presented at this conference. More complete reviews of quark-mixing and the experimental status can be found in Ref. [2,3].

In some extensions to the standard model, neutrinos may have non-zero masses which would open up the possibility of neutrino oscillations. The observed deficit of solar neutrino flux with respect to the standard solar model could be explained by neutrino oscillations. There is also an anomaly in the ratio of muon neutrinos to electron neutrinos observed in atmospheric cosmic rays showers which can also be caused by neutrino oscillations. In this session, three accelerator based experiments presented results of searches for neutrino oscillations.

Neutrino Oscillations

Results from a search for $\nu_\mu \rightarrow \nu_e$ oscillations from the LSND (Liquid Scintillator Neutrino Detector) collaboration were presented during this session [4]. LSND previously reported an excess of events using a $\bar{\nu}_\mu$ flux generated by μ^+ decays at rest (DAR) [5]. This excess can be interpreted as evidence for neutrino oscillations. New independent results using ν_μ from π^+ decay in flight (DIF) were reported here. The ν_e appearance is detected via the charged-current reaction $\nu_e C \rightarrow e^- X$.

The LSND detector [6] consists of a 167 metric tons of liquid scintillator with 1220 eight inch Hamamatsu photomultiplier tubes viewing the volume. Čerenkov and scintillation light are observed in the scintillator which gives information that allow particle identification of the electron candidates as well as the event vertex and direction. Details of the event selection and electron identification for the DIF analysis can be found in Ref. [7].

Two independent analyses of the decay-in-flight data were performed and a total of 40 beam-on electron events with energy in the range $60 < E_e < 200$ MeV were observed. The endpoint of the Michel electron spectrum is at 52.8 MeV. The lower limit on the electron energy was chosen to reduce backgrounds from other beam-related neutrino interactions and background induced by cosmic ray muons. Estimates from beam-off data show a rate increase above electron energies of 200 MeV. The summary of the two analyses and the number of candidate events from the beam-on and beam-off data samples are shown in Table 1. The number of candidate events observed in the combination of the two analyses (OR in the table) is in excess of the 21.9 ± 2.1 events expected from the background. The background is determined from calculations of ν_e contamination in the beam and from the beam-off background. An estimate of the background rate from beam related processes is given in Table 2.

Assuming neutrino oscillations arise from two-generation mixing, the oscillation probability is given by $P_{osc} = \sin^2 2\theta \sin^2(1.27 \Delta m^2 \frac{L}{E_\nu})$ where θ is the mixing angle, $\Delta m^2(\mathrm{eV}^2/c^4)$ is the difference of the squares of the masses of the mass eigenstates, L (m) is the distance from the production of the neutrino to the detector and E_ν is the energy of the neutrino. If the observed excess of events from the DIF analyses is interpreted as an oscillation signal, the observed oscillation probability of $P_{osc} = (2.6 \pm 1.0 \pm 0.5) \times 10^{-3}$ which is consistent with the previously reported $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation evidence from LSND as is shown in Figure 2.

NOMAD (Neutrino Oscillation MAgnetic Detector) and CHORUS (CERN Hybrid Oscillation Research ap-

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Data Set	Beam On/Off	Excess	Eff. (%)	Osc. Prob. ($\times 10^{-3}$)
A	23/114	10.5 ± 4.9	8.4	2.9 ± 1.4
B	25/92	10.1 ± 5.3	13.8	1.7 ± 0.9
AND	8/31	2.7 ± 2.9	5.5	1.1 ± 1.2
OR	40/175	18.1 ± 6.6	16.5	2.6 ± 1.0

Table 1
Comparison of results with statistical errors for the two analyses, A and B, their logical AND and OR. The ratio of beam-on to beam off data collection was 0.07 over a three year period.

Process	Number of Events
$\nu_e C \to e^- X$ (μ Decay-In-Flight)	3.8
$\nu_e C \to e^- X$ (π Decay-In-Flight)	1.6
$\nu_\mu C \to \nu_\mu C \pi^0$	0.3
$\nu_\mu e \to \nu_\mu e$	0.1
Total background	5.8

Table 2
Background estimates assuming an electron selection efficiency of 10% for the $\nu_\mu \to \nu_e$ oscillation search. Efficiencies used in the analyses A and B are energy dependent and differ slightly from these estimates. The beam related background for analysis A is 4.5 ± 0.9 and for analysis B is 8.5 ± 1.7

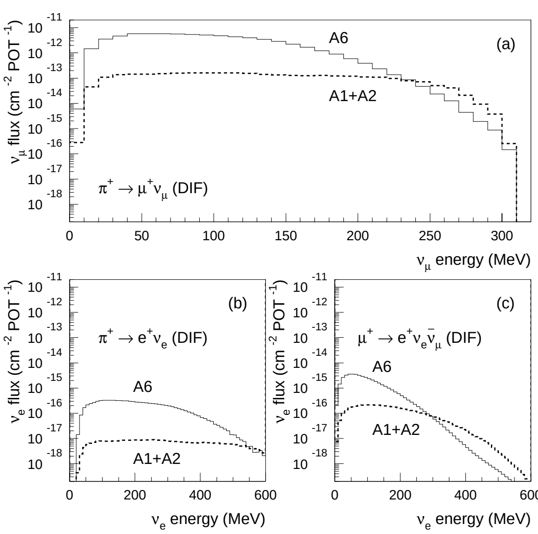

Figure 1. The generated ν_μ and ν_e Decay-In-Flight(DIF) fluxes at the detector. The principle source of the DIF ν_μ is a 30-cm long water target (A6) 1.5 m upstream of a copper beam stop that is 30 m from the detector. Two thin copper targets, A1 and A2, are located 135 m and 110 m upstream of the detector provide small additional contributions to the ν_μ flux. The main beam related background comes form the intrinsic ν_e component of the beam which is shown in plot b and c.

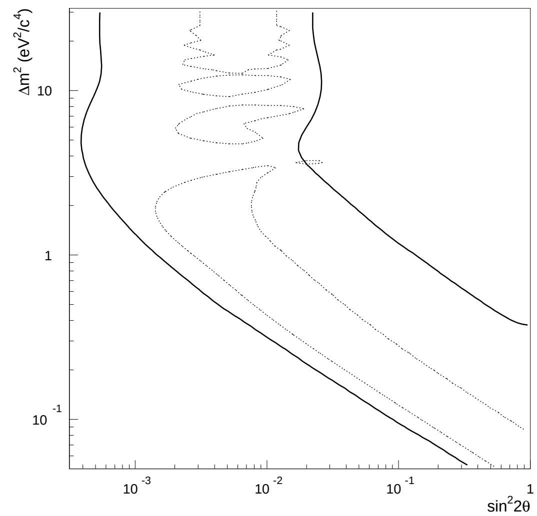

Figure 2. The 95% confidence level region for the Decay-In-Flight (DIF) $\nu_\mu \to \nu_e$ plotted with the favored regions from the LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ Decay-At-Rest (DAR) measurement (dotted contours).

paratUS) are two experiments that have been operating at CERN and have searched for evidence of neutrino oscillations. The beam energy and the detector to source distance limits the sensitivity at low values of Δm^2 making these experiments sensitive to small mixing angles only at relatively large values of Δm^2.

The CHORUS collaboration presented preliminary results from a pilot analysis of their 1994 run [8]. The goal of the CHORUS experiment is to search for ν_μ to ν_τ oscillations through the appearance of the ν_τ in their ν_μ beam. The experiment has an 800 kilogram emulsion target followed by a fiber tracker, magnetic spectrometer, calorimeter and muon spectrometer. A ν_τ is identified via its charged current interaction in the emulsion which produces a τ. The τ^- is identified with information from the downstream spectrometer and the observation of a charged track in the emulsion with a kink indicating its point of decay. CHORUS probes small mixing angles for Δm^2 differences greater than about 10 (eV)^2. For large Δm^2 their preliminary limit on the mixing angle is $\sin^2 2\theta \leq 5.4 \times 10^{-3}$ (90% C.L.) based on data from the pilot analysis. They expect to be able to scan the remaining emulsion using automatic scanning machines which will reduce the analysis time. After the analysis of the entire data sample 1994-1997 they expect to improve the mixing angle limit to $\sin^2 2\theta \leq 2 \times 10^{-4}$ if no candidate events are observed.

The NOMAD experiment has also done a search for the oscillation $\nu_\mu \to \nu_\tau$ through the appearance of ν_τ at the CERN SPS wide band ν_μ beam [9]. The τ lepton produced is identified via its decay using kinematic criteria. The τ track itself is not resolvable in the NOMAD apparatus [10]. The NOMAD detector has been optimized for the identification of electrons and muons and for resolution in the measurement of energy flow and of charged particle momenta. They also search for the oscillation $\nu_\mu \rightarrow \nu_e$ via the appearance of excess ν_e events.

The NOMAD collaboration has analyzed their 1995 data sample which corresponds to 8×10^{18} protons on target or $2 \times 10^5 \nu_\mu$ charged current interactions observed in the fiducial volume of the detector. There were no events observed in the 1995 data set for all τ decays channels studied ($\pi^- \nu_\tau$, $e^- \bar{\nu}_e \nu_\tau$ and $\mu^- \bar{\nu}_\mu \nu_\tau$). The expected number of observed τ decays (N_τ) corresponding to a signal from neutrino oscillations with a probability of oscillation $P_{osc}(\nu_\mu \rightarrow \nu_\tau) = 1$ is 1258. Considering the estimated background and the systematic uncertainty on the number of expected events [11], they set a limit on the mixing angle for large Δm^2 of $\sin^2 2\theta < 4 \times 10^{-3}$ (90% C.L.). Assuming no candidates are observed, NOMAD expects to extend this limit by an order of magnitude following the completion of the analysis of their full data sample.

NOMAD has also performed a search for $\nu_\mu \rightarrow \nu_e$ oscillations. If the oscillation probability $P_{osc}(\nu_\mu \rightarrow \nu_e)$ is on the order of 10^{-3} then the observed ν_e flux would increase by approximately 10% over the flux expected from other processes. Precise knowledge of the ν_e component of the beam is very important in the measurement. They set a preliminary limit of $\sin^2 2\theta < 2 \times 10^{-3}$ (90% C.L.) for large values of Δm^2. Studies of the systematic errors in this measurement are in progress. This preliminary measurement excludes part of the region indicated by the LSND results.

Taus Decays

Recent measurements from the LEP experiments on hadronic τ decay were presented at this session [12]. The LEP experiments have collected more than 160 pb^{-1} per experiment while running at a center-of-mass energy near M_Z. This corresponds to approximately 200,000 τ pairs in each experiment. They have made measurements of τ production, τ decays and the ν_τ mass [13]. Aleph has an preliminary upper limit on the ν_τ mass from 3-prong and 5-prong decays [14]. Their limit is $m_{\nu_\tau} < 18.2$ MeV/c^2 (90% C.L.). Aleph has also measured the spectral function of non-strange τ vector current final states [15]. The dominant two-pion and four-pion τ decay channels ($\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$, $\tau^- \rightarrow \pi^- 3\pi^0 \nu_\tau$ $\tau^- \rightarrow 2\pi^- \pi^+ \pi^0 \nu_\tau$) were used in the analysis. They found good agreement between the vector spectral function for τ^- and the isovector part of the total cross section of $e^+e^- \rightarrow$ hadrons.

The OPAL collaboration has a new limit on branching ratio limit for 7-prong τ decays,
$\mathrm{Br}(\tau^- \rightarrow 4\pi^- 3\pi^+ n\pi^0 n\gamma \nu_\tau (n \geq 0)) < 1.8 \times 10^{-5}$
[16]. This measurement includes a total relative systematic error of 4.3% which comes mainly from the uncertainty of the phase space modeling of the 7-prong final state.

CLEO has made precision measurements of the Michel parameters ρ, ξ, and δ in the decays $\tau^\mp \rightarrow l^\mp \nu \bar{\nu}$ and the tau neutrino helicity parameter h_{ν_τ} in $\tau^\mp \rightarrow \pi^\mp \pi^0 \nu$ decay [17]. From a data sample of 3.02×10^6 tau pairs they report the following:

$\rho = 0.747 \pm 0.010_{\mathrm{stat.}} \pm 0.006_{\mathrm{sys.}}$,
$\xi = 1.007 \pm 0.040_{\mathrm{stat.}} \pm 0.015_{\mathrm{sys.}}$,
$\xi\delta = 0.745 \pm 0.026_{\mathrm{stat.}} \pm 0.009_{\mathrm{sys.}}$, and
$h_{\nu_\tau} = -0.995 \pm 0.010_{\mathrm{stat.}} \pm 0.003_{\mathrm{sys.}}$.

The results are in good agreement with the Standard Model V-A values and represent an improvement on the previous world averages for these quantities. The accuracy of the measurements remains limited by statistics, so there is a possibility that higher luminosity machines will be able to improve on the current accuracy [18].

Kaons: CP Violation and Rare Decays

Recent results from BNL experiment E787 were also reported at this session [19]. The details of the apparatus can be found in Ref. [21]. The collaboration reports the first observation of the decay $K^+ \rightarrow \pi^+ \gamma\gamma$ which can be used to test chiral perturbation theory [20]. A total of 31 events were observed with a background of 5.1 ± 3.3 events in the π^+ momentum range from 100 MeV/c to 180 MeV/c. No $K^+ \rightarrow \pi^+ \gamma\gamma$ decays were observed in the π^+ momentum region greater than 215 MeV/c. They measured a branching ratio $\mathrm{Br}(K^+ \rightarrow \pi^+ \gamma\gamma$, 100 MeV/c $< P_{\pi^+} <$ 180 MeV/c$) = (6.0 \pm 1.5_{stat} \pm 0.7_{sys}) \times 10^{-7}$. The π^+ momentum spectrum was compared to the predictions of chiral perturbation theory and give a best fit value for $\hat{c} = 1.80^{0.63}_{0.64}$ with unitarity corrections. The total branching ratio is estimated assuming this same spectral shape: $\mathrm{Br}(K^+ \rightarrow \pi^+ \gamma\gamma) = (1.1 \pm 0.3 \pm 0.1) \times 10^{-6}$.

The E787 Collaboration has also observed the decay $K^+ \rightarrow \pi^+ \mu^+ \mu^-$, an electromagnetically-induced semi-leptonic weak decay. They have made a measurement of the branching ratio [22] $\mathrm{Br}(K^+ \rightarrow \pi^+ \mu^+ \mu^-) = (5.0 \pm 0.4_{stat} \pm 0.7_{sys} \pm 0.6_{th}) \times 10^{-8}$. Comparing this result with the predictions of chiral perturbation theory, they find a best fit value the parameter $w_+ = 1.07 \pm 0.07$. This parameter can be compared to a previous measurement using the decay $K^+ \rightarrow \pi^+ e^+ e^-$ [23] where $w_+ = 0.89^{+0.24}_{-0.14}$. Theory predicts values for this parameter that range from 0.49 to 2.04 [24].

A status report on the E787 search for the rare decay $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ was presented [19]. This decay mode is sensitive to $|V_{td}|$, the element of the CKM matrix that describes the coupling of top to down quarks. Projections for this decay mode indicated that the experiment would soon have a single event sensitivity in the range predicted by the standard model. (The standard model predicts Br($K^+ \rightarrow \pi^+ \nu\bar{\nu}$)=$0.6 - 1.5 \times 10^{-10}$ [25].) Since the time of this conference, an event consistent with the signature expected for this interesting rare kaon decay ($K^+ \rightarrow \pi^+ \nu\bar{\nu}$) has been reported by E787[26].

There have been a number of proposals for new experiments to explore kaon physics. An experiment described in this session proposes to test CPT invariance at the Planck scale using a 25 GeV RF separated K^+ beam to produce K^0 by charge exchange [27]. The resulting beam is nearly pure K^0 and a good place to measure $K_L \rightarrow \pi^+\pi^-$,$K_S \rightarrow \pi^+\pi^-$ interference [28]. Note that it has been suggested that spontaneous CPT-violation could occur in certain string theory models [29].

Direct CP violation in K decay can be observed through K_L and K_S decays into $\pi^+\pi^-$ and $\pi^0\pi^0$. The parameter (ϵ'/ϵ) is derived from the double ratio of these decays. The current experimental situation for the measurement of Re(ϵ'/ϵ) is rather cloudy. At CERN, NA31 measured Re(ϵ'/ϵ) = $(23 \pm 7) \times 10^{-4}$ [30] which indicates CP-violation while the Fermilab experiment E731 measured Re(ϵ'/ϵ) = $(7.4 \pm 5.2 \pm 2.9) \times 10^{-4}$[31] which is consistent with $\epsilon'/\epsilon = 0$. A new round of experiments will make precision measurements $\delta(\epsilon'/\epsilon) \approx 1 \times 10^{-4}$. The theoretical expectation for ϵ'/ϵ is less than 10^{-3}, for $m_s(m_c) = \mathcal{O}(150\text{MeV})$; for smaller values of m_s, however, ϵ'/ϵ could be somewhat larger [2].

The KTeV experiment has collected a large data sample over the past year and a status report was given at this session [32]. The aim of the experiment is to make a measurement of direct CP violation in the K system and to study rare kaon decays. Upon completion of the analysis of their data, they expect to have a statistical uncertainty of about 10^{-4} and a systematic error that is about one half of the statistical error.

KTeV also presented results on a search for a light gluino. A SUSY model predicts the existence long-lived hadrons that contain gluinos [33]. The R^0 would be the lightest bound state of a gluon and a light gluino. The state decay $R^0 \rightarrow \tilde{\gamma}\rho, \rho \rightarrow \pi^+\pi^-$. They searched for $\pi^+\pi^-$ events with high mass (invariant mass greater than 648 MeV) in one day of data taking and observed no events. The KTeV limits severely restricts the lightest stable SUSY state in the theory. Depending on the photino mass, they exclude the R^0 in the mass range of 1.2 – 4.6 GeV and lifetime range of $2 \times 10^{-10} - 7 \times 10^{-4}$ seconds. [34].

The KTeV collaboration presented several preliminary results on rare decays at this session [35]. The analysis of their new data from the 1996-1997 run

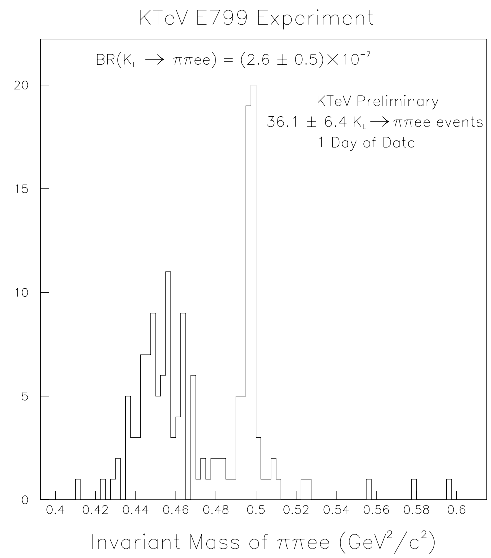

Figure 3. Preliminary results from KTeV showing the invariant mass spectrum for the decay $K_L^0 \rightarrow \pi^+\pi^-e^+e^-$. The data is from one day of KTeV(E799) of running.

is just beginning. They presented results on a one day special run to search for the mode $K_L \rightarrow \pi^0\nu\bar{\nu}$. This mode offers one of the more interesting channels for measuring direct CP violation, however, it also presents difficult experimental challenges. The standard model prediction for the branching ratio is Br($K_L \rightarrow \pi^0\nu\bar{\nu}$) = $(2.8 \pm 1.7) \times 10^{-11}$ [2] and is directly related to the height of the unitarity triangle. The main errors in the prediction come from the uncertainties in the CKM parameters. The analysis of the data from this special run yielded one event in the region of interest that is consistent with background and a preliminary branching ratio limit Br($K_L \rightarrow \pi^0\nu\bar{\nu}$) < 1.8×10^{-6}. The previous limit comes from the FNAL experiment E731 [36].

Another K_L decay that is of great interest for its potential as a method for measuring CP violation is the mode $K_L \rightarrow \pi^+\pi^-e^+e^-$. The interference of the CP-violating inner bremsstrahlung process with the direct emission of a virtual photon should generate an asymmetry in ϕ, the angle between the decay planes of the e^+e^- and the $\pi^+\pi^-$ in the K_L center-of-mass frame. The asymmetry is projected to be about 14%. In a preliminary analysis of one day of data, KTeV observed a signal of 36.1 ± 6.4 $K_L \rightarrow \pi^+\pi^-e^+e^-$ events. The main background comes from $K_L \rightarrow \pi^+\pi^-\pi^0$ where the $\pi^0 \rightarrow \gamma e^+e^-$. They have measured a preliminary branching ratio for this decay of $(2.6 \pm 0.5) \times 10^{-7}$ using the matrix element described in Ref. [37]. The measurement has a strong dependence on the choice of decay model.

Decay Mode	Current E687 Limit
$D^+ \to \pi^+ e^+ e^-$	11×10^{-5}
$D^+ \to K^+ e^+ e^-$	20×10^{-5}
$D^+ \to \pi^+ \mu^+ \mu^-$	8.9×10^{-5}
$D^+ \to K^+ \mu^+ \mu^-$	9.7×10^{-5}
$D^+ \to \pi^+ \mu^+ e^-$	13×10^{-5}
$D^+ \to K^+ \mu^+ e^-$	12×10^{-5}
$D^+ \to \pi^+ \mu^- e^+$	11×10^{-5}
$D^+ \to K^+ \mu^- e^+$	13×10^{-5}
$D^+ \to \pi^- e^+ e^+$	11×10^{-5}
$D^+ \to K^- e^+ e^+$	12×10^{-5}
$D^+ \to \pi^- \mu^+ \mu^+$	8.7×10^{-5}
$D^+ \to K^- \mu^+ \mu^+$	12×10^{-5}
$D^+ \to \pi^- \mu^+ e^+$	11×10^{-5}
$D^+ \to K^- \mu^+ e^+$	13×10^{-5}

Table 3
Current limits on rare and standard-model forbidden D^+ decays from the Fermilab experiment E687 [42].

Charm Production and Decay

Charm results from LEP, Fermilab and CLEO were presented at the conference. The Fermilab Experiment E687, a fixed target photoproduction experiment, presented results based on 10^5 reconstructed charm decays [38]. The charm physics contributions from this experiment include competitive charm particle lifetime measurements, and form factors and relative branching ratio measurements for semileptonic decay modes. They have measured the Cabibbo suppressed, semileptonic decays $D^0 \to \pi^- \ell^+ \nu$ [39] and $D^+ \to \rho^0 \ell^+ \nu$ [40]. These decays can be used to compare the form factors between Cabibbo allowed and Cabibbo suppressed decays. They find the relative branching ratio:

$$\frac{\mathrm{Br}(\mathrm{D}^0 \to \pi^- \ell^+ \nu)}{\mathrm{Br}(\mathrm{D}^0 \to \mathrm{K}^- \ell^+ \nu)} = 0.101 \pm 0.020_{stat} \pm 0.003_{sys}.$$

They have also observed the first statistically significant signal for the vector meson Cabibbo suppressed decay $D^+ \to \rho^0 \mu^+ \nu$. The relative branching ratio is

$$\frac{\mathrm{Br}(\mathrm{D}^+ \to \rho^0 \mu^+ \nu)}{\mathrm{Br}(\mathrm{D}^+ \to \mathrm{K}^{*-} \mu^+ \nu)} = 0.079 \pm 0.019_{\mathbf{stat}} \pm 0.013_{\mathbf{sys}}.$$

They presented a measurement of

$$\frac{\Gamma(D^0 \to K^- \mu^+ \nu_m u)}{\Gamma(D^0 \to K^- \pi^+)} = 0.852 \pm 0.034_{\mathbf{stat}} \pm 0.02_{\mathbf{sys}}.$$

and have studied multibody hadronic decays of charm mesons and reported evidence for $D^+, D_s^+ \to \pi^- \pi^- \pi^+ \pi^+ \pi^+$ [41]. They presented a long list of limits on rare and standard-model forbidden semileptonic decay modes of the D^+ meson which are shown in Table 3. The decays modes are either flavor changing neutral current (FLNC): $D^+ \to h^+ \ell^+ \ell^-$, lepton family number violating (LFNV): $D^+ \to h^+ \ell_1^+ \ell_2^-$, or lepton number violating (LNV): $D^+ \to h^- \ell_1^+ \ell_{1,2}^+$. The limits for most of the modes are a factor of 2-70 improvement than previous limits.

The FOCUS experiment (E831), an extension of E687 with an upgraded spectrometer, took data during the 1997 fixed target run at Fermilab. This experiment is expected to produce a sample of 10^6 reconstructed charm decays. With this new data sample, they will be able update the physics results from E687 and to measure the absolute branching ratio $Br(D^0 \to K^- \pi^+)$ to 3% and the branching ratio $Br(\Lambda_c \to pK^- \pi^+)$ to 20%. They plan to study the charm baryons and to examine charm production dynamics. They will also have a sensitivity to CP-violating asymmetries in the charm sector at the level of a few percent. The data collection phase ended in the summer of 1997 and the collaboration expects to present its first results in the summer of 1998.

The CLEO Collaboration presented charm results based on 4.8 fb^{-1} of data collected at the $\Upsilon(4S)$ and in the continuum below the Υ(4S) [43]. The cross section for charm production at CLEO is $\sigma(c\bar{c}) \approx 1$nb. At this conference they presented results on the measurement of ratio of hadronic form factors in the semileptonic decays of charmed mesons. It is possible to extract the form factor ratio from the measurement of the following:

$$R_\pi = \frac{D^+ \to \pi^0 \ell^+ \nu}{D^+ \to \bar{K}^0 \ell^+ \nu}.$$

R_π is proportional to $|f_+^\pi(0)/f_+^K(0)|^2 |V_{cd}/V_{cs}|^2$. They find:

$$R_\pi = 0.046 \pm 0.014 \pm 0.017$$

yielding
$|f_+^\pi(0)/f_+^K(0)|^2 = 0.9 \pm 0.3 \pm 0.3$ assuming $|V_{cd}/V_{cs}|^2 = 0.051 \pm 0.001$. They also presented a 90% confidence level upper limit on the measurement of
$R_\eta = \frac{D^+ \to \eta \ell \nu}{D^+ \to \pi^0 \ell \nu} < 1.5$.

CLEO also reported the observation of the decay mode $D_s^+ \to \omega \pi^+$. This final state could be produced through the annihilation decay of the D_s or through final state interactions. The observed branching ratio $\mathrm{Br}(D_s^+ \to \omega \pi^+) = (0.27 \pm 0.12)\%$
is consistent with non-resonant rescattering models [44], annihilation decay or a combination of the two [45].

CLEO presented the first observation of B mesons decaying into the charmed strange baryons Ξ_c^0 and Ξ_c^+. They determined the product branching fractions

$$\mathrm{Br}(\bar{B} \to \Xi_c^0\ X) BR(\Xi_c^0 \to \Xi^- \pi^+) = (0.144 \pm 0.048_{\mathbf{stat.}} \pm 0.021_{\mathbf{sys.}}) \times 10^{-3}$$

and

$$\mathrm{Br}(\bar{B} \to \Xi_c^+ X) BR(\Xi_c^+ \to \Xi^- \pi^+ \pi^+) = (0.453 \pm 0.096_{\mathbf{stat.}}\ {}^{+0.085}_{-0.065\mathbf{sys.}}) \times 10^{-3}.$$

Two production mechanisms, $b \to c\bar{u}d$ and $b \to c\bar{c}s$, are consistent with the measured Ξ_c^0 and Ξ_c^+ momentum spectra [46].

The LEP collaborations have many results on the production of charm hadrons [47]. Measurements of charm anti-charm production at LEP indicate that the world average for $\mathrm{R}_c = 0.1719 \pm 0.0053$ is now consistent with the Standard Model prediction of 0.172. It is difficult to study the details of charm fragmentation functions at LEP and the results presented on the fragmentation function are compatible with a variety of models. The production of P-wave charm mesons has been studied and there have been some interesting observations including the measurement of the D_{s1}^{+} production rate from OPAL [48]. The measured production fractions are consistent with current models of heavy-quark fragmentation.

Beauty: Production, Decays and Prospects

The L3 Collaboration reported measurements of the inclusive production of J, ψ' and χ_c mesons in hadronic Z decays [49,50]. The measured branching fractions from L3 are:

$\mathrm{Br}(\mathrm{Z} \to \mathrm{J} + \mathrm{X}) = (3.40 \pm 0.23_{\mathrm{stat.}} \pm 0.27_{\mathrm{sys.}}) \times 10^{-3}$,
$\mathrm{Br}(\mathrm{Z} \to \psi' + \mathrm{X}) = (1.6 \pm 0.5_{\mathrm{stat.}} \pm 0.3_{\mathrm{sys.}}) \times 10^{-3}$,
$\mathrm{Br}(\mathrm{Z} \to \chi_{c1} + \mathrm{X}) = (2.7 \pm 0.6_{\mathrm{stat.}} \pm 0.5_{\mathrm{sys.}}) \times 10^{-3}$,

which are in agreement with previous measurements from other experiments [51,52]. No clear χ_{c2} signal was observed, and they set an upper limit at 90% C.L. of $\mathrm{Br}(\mathrm{Z} \to \chi_{c2} + \mathrm{X}) < 3.2 \times 10^{-3}$.

The production of Υ mesons in the decays of the Z^0 at LEP is expected to be small. However, color octet production models [56] which have been used to explain large Υ production seen at CDF [57] predict larger production rates of Υ from Z^0 decays than color singlet production alone. The L3 collaboration reported that they observed no signal for the decay $Z \to \Upsilon X$; $\Upsilon \to l^+ l^- (l = e, \mu)$. Upper limits at the 95% confidence level are set on the following Z branching fractions:

Br $(Z \to \Upsilon(1S)X) < 5.5 \times 10^{-5}$,
Br $(Z \to \Upsilon(2S)\mathrm{X}) < 13.9 \times 10^{-5}$,
Br $(Z \to \Upsilon(3S)X) < 9.4 \times 10^{-5}$.

This is consistent with a previous upper limit set by the Delphi collaboration [54]. Opal has made a previous measurement of $\mathrm{Br}(Z \to \Upsilon X) = (10 \pm 4 \pm 1) \times 10^{-5}$ [55] which agrees within errors with the predicted branching ratio when one assumes contributions from both color singlet and color octet production mechanisms.

LEP limits on B_c production are now close to the theoretical predictions [49,51,58,59]. Aleph has seen one event which could be a candidate for a B_c in the decay mode $B_c \to J/\psi \mu^+ \nu$. The event was found by scanning events in the $\psi X^{\pm}$ sample with a mass above the $B^{\pm}$ mass and is described in detail in Reference [59].

Aleph presented a recent measurement of $|V_{cb}|$ and form factors in exclusive semi-leptonic B decays [60, 61]. Heavy quark effective theory (HQET) makes it possible to extract an accurate value of $|V_{cb}|$ from measurements of the decay rate at the point of zero recoil of the daughter meson in exclusive semileptonic B meson decays. Several experiments have already made very accurate measurements of $|V_{cb}|$ using the exclusive semi-leptonic decays $\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}_\ell$ [62,63]. The form factors as measured by Aleph in $\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}_\ell$ and $\bar{B}^0 \to D^+ \ell^- \bar{\nu}_\ell$ agree within the experimental uncertainty as is predicted by heavy quark effective theory. $|V_{cb}|$ was measured without relying on linear parameterization of the form factor and was found to be $|V_{cb}| = (34.4 \pm 1.6_{\mathrm{stat}} \pm 2.3_{\mathrm{syst}} \pm 1.4_{\mathrm{th}}) \times 10^{-3}$. The slope of the Isgur-Wise function was measured to be $a_0^2 = 0.30 \pm 0.12_{\mathrm{stat}} \pm 0.14_{\mathrm{syst}} \pm 0.13_{\mathrm{th}}$. The Aleph measurements for the form factors are in good agreement with the other measurements and with a recent measurement CLEO collaboration [64]. A combined world average for $|V_{cb}|$ was recently calculated from the exclusive decays for ICHEP '96 and can be found in Reference [3].

Recent results from CLEO on the decays of B mesons were presented at this session [65]. They have new results on a number of topics including $b \to c$ transitions, where they have made high statistics measurements of $B \to D^{(*)} X$ branching ratios: [66].

$\mathrm{Br}(B \to D^0 X) = (0.636 \pm 0.014 \pm 0.019 \pm 0.018)$,
$\mathrm{Br}(B \to D^+ X) = (0.235 \pm 0.009 \pm 0.009 \pm 0.024)$,
$\mathrm{Br}(B \to D^{*0} X) = (0.247 \pm 0.012 \pm 0.018 \pm 0.018)$,
$\mathrm{Br}(B \to D^{*+} X) = (0.239 \pm 0.011 \pm 0.014 \pm 0.009)$.

They also reported new measurements of the branching ratios [67]:

$\mathrm{Br}(B^0 \to D^{*+} \pi^-) = (2.81 \pm 0.11 \pm 0.21 \pm 0.05) \times 10^{-3}$,
$\mathrm{Br}(B^- \to D^{*0} \pi^-) = (4.34 \pm 0.33 \pm 0.34 \pm 0.18) \times 10^{-3}$

using the technique of partial reconstruction to enhance the statistics.

CLEO has searched for evidence of the color-suppressed B hadronic decay processes $\bar{B}^0 \to D^0 (D^{*0}) X^0$, where X^0 is one of the light neutral mesons π^0, ρ^0, η, η' or ω. No signal was observed in any channel. These decays proceed via an internal spectator diagram and are expected to be color-suppressed. They have been able, therefore, to set 90 % C.L. upper limits on these modes. The results are listed in Table 4. These limits are improvements over previous limits but are still larger than theoretical predictions.

The factorization hypothesis for decays with internal W-emission can be tested through the measurement of the decay amplitudes $B \to J/\psi K^{(*)}$. In addition, the decay $B^0 \to J/\psi K^{*0}; K^{*0} \to K_S^0 \pi^0$, a mixture of CP-odd and CP-even eigenstates, might offer another way to measure the angle β of the unitarity triangle if one CP eigenstate dominates or if the two CP eigenstates can be separated. CLEO has made the first full angular analysis of the color-suppressed modes $B^0 \to J/\psi K^{*0}$ and $B^+ \to J/\psi K^{*+}$ providing a complete determination of the decay amplitudes. They have found that the parity-odd component of the decay amplitude is small which implies that this decay could be useful for

Decay Mode	CLEO Limit
$B^0 \to D^0\pi^0$	$< 1.2 \times 10{-}4$
$\bar{B}^0 \to D^{*0}\pi^0$	$< 4.4 \times 10{-}4$
$\bar{B}^0 \to D^0\pi^0$	$< 3.9 \times 10{-}4$
$\bar{B}^0 \to D^{*0}\rho^0$	$< 5.6 \times 10{-}4$
$\bar{B}^0 \to D^0\eta$	$< 1.3 \times 10{-}4$
$\bar{B}^0 \to D^{*0}\eta$	$< 2.6 \times 10{-}4$
$\bar{B}^0 \to D^0\eta'$	$< 9.3 \times 10{-}4$
$\bar{B}^0 \to D^{*0}\eta'$	$< 1.9 \times 10{-}3$
$\bar{B}^0 \to D^0\omega$	$< 5.1 \times 10{-}4$
$\bar{B}^0 \to D^{*0}\omega$	$< 7.4 \times 10{-}4$

Table 4
90% C.L. upper limits on branching ratios for color-suppressed modes. [68]

future CP violation studies at the B factories. The branching fractions for these modes were also measured: $\mathrm{Br}(B^+ \to J/\psi K^+ = 1.02 \pm 0.08 \pm 0.07) \times 10^{-3}$,
$\mathrm{Br}(B^0 \to J/\psi K^0 = 0.85^{0.14}_{0.12} \pm 0.06) \times 10^{-3}$,
$\mathrm{Br}(B^+ \to J/\psi K^{*+} = 1.41 \pm 0.23 \pm 0.24) \times 10^{-3}$,
$\mathrm{Br}(B^0 \to J/\psi K^{*0} = 1.32 \pm 0.17 \pm 0.17) \times 10^{-3}$,
and R$= \frac{\mathrm{Br}(B \to J/\psi K^*)}{\mathrm{Br}(B \to J/\psi K)} = 1.45 \pm 0.20 \pm 0.17$.

From a data sample of 3.3 M $B\bar{B}$ events CLEO has been able to observe a number of rare decay modes of the B meson. One of the more interesting classes of rare B decays is that of the charmless B decay. In particular, the mode $\pi\pi$ is one of the classic channels which will be used in the measurement of the angle α in the CKM unitarity triangle. There is some concern, however, that large penguin contributions to the decay $B^0 \to \pi^+\pi^-$ will make it difficult to extract sin2α from the measured asymmetry. CLEO had previously published a limit on the combined branching ratio $\mathrm{Br}(B^0 \to \pi^+\pi^- + K^+\pi^-) = (1.8^{+0.6+0.2}_{-0.5-0.3} \pm 0.2) \times 10^{-5}$ [70]. With 30% more data and an analysis that is 20% more efficient, CLEO presented new results on charmless hadronic decays of the B in this session [71]. The observed a total number of events in their final sample is as follows: in the $K\pi$ decay channel there are $N_{K\pi} = 21.7^{+6.8}_{-6.0}$; in the $\pi\pi$ decay channel the number is $N_{\pi\pi} = 10.0^{+6.0}_{-5.1}$. The mass spectrum for the $\pi^+\pi^-$ channel is shown in Figure 4 and the results of the fit to the observed number of signal events is shown in Figure 5. CLEO has measured the following branching fractions [72] which indicate that $b \to sg$ penguins contributions are important in charmless hadronic B decays.

$\mathrm{Br}(B^0 \to K^+\pi^-) = (1.5^{+0.5+0.1}_{-0.4-0.1} \pm 0.1) \times 10^{-5}$,
$\mathrm{Br}(B^0 \to \pi^+\pi^-) < (1.5 \times 10^{-5})$ (90% C.L.),
$\mathrm{Br}(B^0 \to K^+K^-) < (0.43 \times 10^{-5})$ (90% C.L.).

CLEO has made measurements or set limits for a large number of rare decay modes of the B. A summary of their results is shown in Figure 6. Interesting

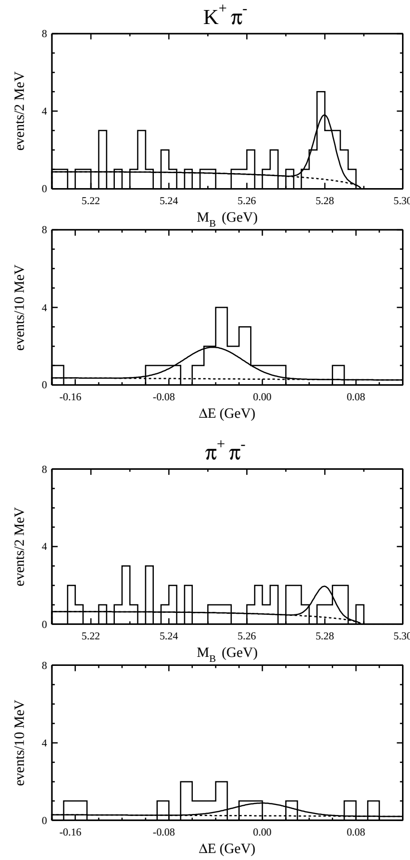

Figure 4. The beam constrained mass and $\Delta E = E_B - E_{beam}$ for the $K^+\pi^-$ and $\pi^+\pi^-$ channels.

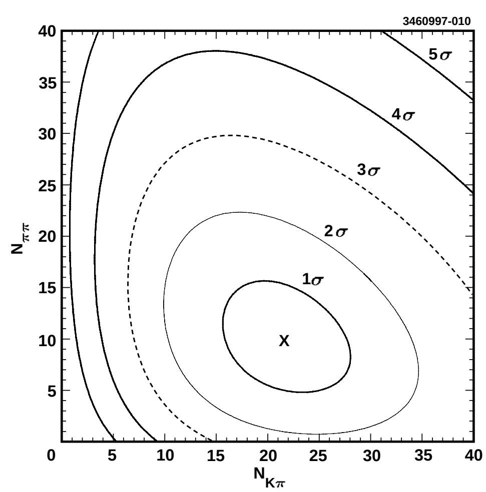

Figure 5. The contours -2ln$\mathcal{L}$ from a maximum likelihood fit to the $N_{K^\pm\pi^\mp}$ and $N_{\pi^+\pi^-}$.

among the new results is the measurement of the inclusive decay $B \rightarrow \eta' X_s$. The preliminary measurement of the branching fraction yields a larger than expected result: $\mathrm{Br}(B \rightarrow \eta' X_s) = (5.5 \pm 1.5 \pm 1.1) \times 10^{-4}$ for high momentum η' $(2.0 < p_{\eta'} < 2.7$ GeV).

The B Factories

Within the context of the standard model, it is expected that will be large CP-violating effects in the B system. Several new experiments will begin data taking within the next few years that will have the potential to measure CP violating effects in the B system. In this session, we heard reports on the status of a few experiments that are designed to explore CP violation in the B system.

Two asymmetric B factories, one at SLAC and one at KEK, will begin operation within the next few years. The detectors BELLE and BABAR [73] are under construction.These detectors are designed to have silicon vertex detectors and good particle identification. BABAR will use a DIRC (Detection of Internally Relected Čerenkov light) for their particle identification, while BELLE has chosen a threshold aerogel Čerenkov counter design [74]. The first goal of these experiments will be to measure $\sin 2\beta$ through the "golden" mode $B^0 \rightarrow J/\psi K^0_S$. Operating with a luminosity of $3 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, they will be able to reach an error on $\sin 2\beta$ of approximately 0.10 using this mode alone. Other modes such as $B^0 \rightarrow J/\psi K^{*0}$ and $B^0 \rightarrow J/\psi K^0_L$can be used to increase the sensitivity in this measurement. Measuring the angle α will require good particle indentification at high momentum and an understanding of the penguin contributions in the decay $B^0 \rightarrow \pi^+\pi^-$. These two facilities, along with the CLEO III detector [75] will carry out a large program in B physics during the next decade. The Hera-B experiment, which will use a wire target in the halo of the HERA beam, will begin data taking soon.

Hadron colliders produce copious numbers of $b\bar{b}$ pairs. CDF has demonstrated that with excellent tracking and proper triggering, many B physics studies can be made at hadron colliders [76]. Upgraded CDF and D0 detectors will begin data taking within a few years. The completion of the Main Injector will enable the Tevatron to operate with higher luminosity during the upcoming run (Run II). CDF has extrapolated from their current data sample to estimate the number of events expected during Run II. With 20 times the luminosity, they expect to reconstruct 10,000 $B^0 \rightarrow J/\psi K^0_S$ with an effective tagging efficiency $\epsilon D^2 \approx 7\%$ [77]. CDF will also have a two-track hadronic B trigger that will enable them to study $B^0 \rightarrow \pi^+\pi^-$ decays. Unfortunately, neither CDF nor D0 will have a particle identification system with adequate $K - \pi$ separation to cleanly distinguish $K\pi$ from $\pi\pi$.

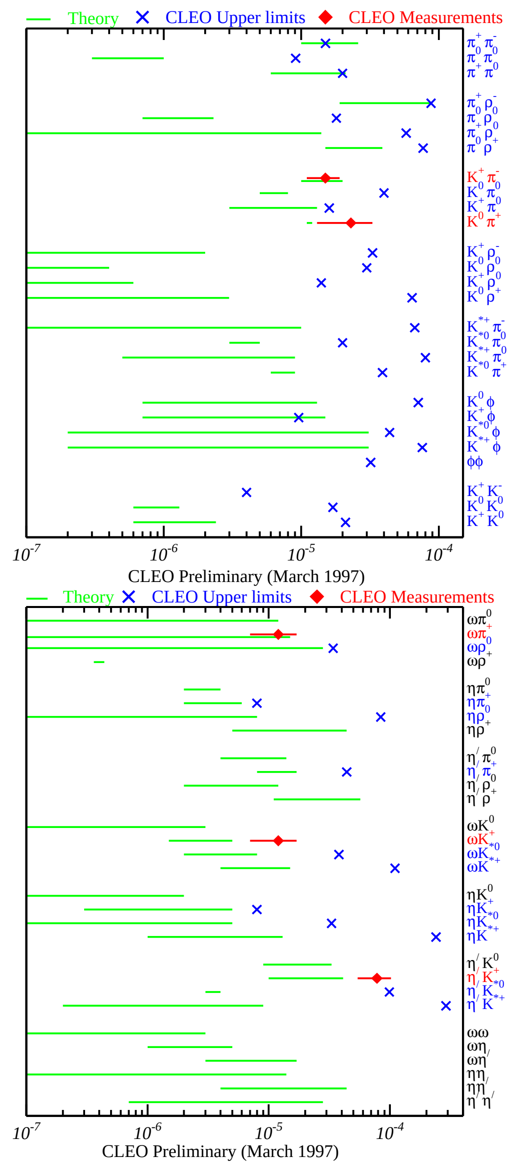

Figure 6. A summary of results and expectations for rare B decay measurements from the CLEO.

Planning for second generation B factories are already underway. The e^+e^- machines are developing plans for luminosity upgrades. Precision measurements and the observation of rare decay modes require large statistics. Hadron colliders provide an excellent laboratory for these measurements. One of the most important aspects of operating at a hadron machine is the trigger. Traditionally, lepton triggers have been used, but it is extremely important for a B experiment to have the capability to trigger on all hadronic decay modes. The detectors must also have exellent vertex detectors and excellent particle identification. Two forward colleder detectors have been proposed as second generation B experiments, one at the Tevatron at Fermilab and one at the LHC at CERN. The Fermilab experiment, BTeV, will have a vertex detector made of silicon pixels, a Level-1 vertex trigger and a two-arm spectrometer each containing forward tracking devices, a RICH detector, an electromagnetic calorimeter and a muon detector [78,79]. The LHC-B will have a similar layout [80] with one arm. These detectors will have excellent time resolution and will be ideal for the study of B_s physics.

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